New Approaches and Small-scale Experiments

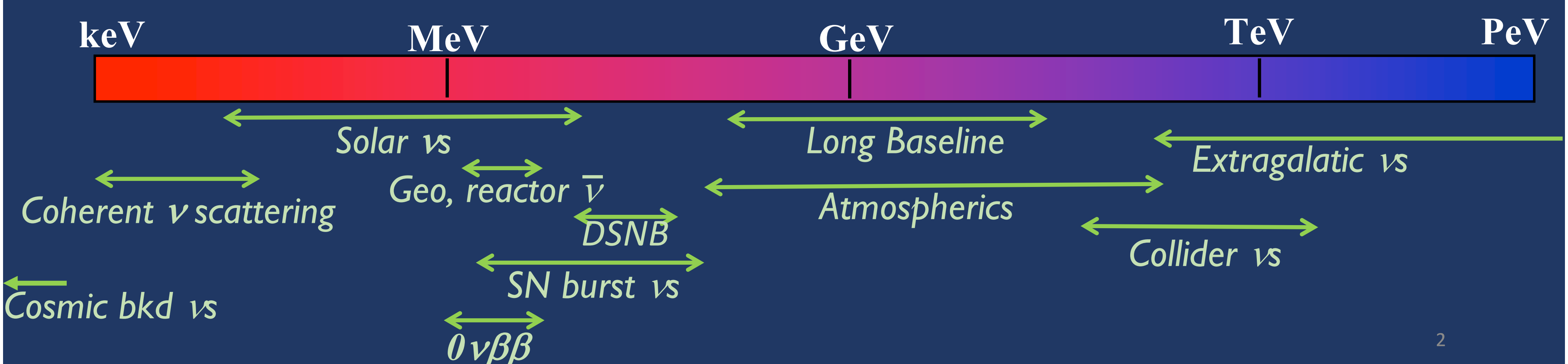
- Scope
- Overview of the Program
- (Very Small) Set of Examples and Opportunities

Josh Klein , U. Penn
P5 Town Hall
March 22, 2023

SNOWMASS Neutrino Frontier

Need for Programmatic Breadth

- Opportunities for advances in the neutrino sector are entwined with opportunities in many other sectors, spanning all of the Snowmass Frontiers and multiple scales of time, size and cost. **A future program with a healthy breadth and balance of physics topics, experiment sizes, and timescales, supported via a dedicated, deliberate, and ongoing funding process, is highly desirable.** This process should also provide opportunities to explore and eventually resolve existing and future neutrino-related anomalies and to develop instrumentation and new beam technologies that will have a broad impact across the field. Furthermore, connections between programs should be carefully curated to optimize science output.



Scope

N_{exp} ~ 1/d ~ 1/$...have limited scope as much as reasonable here

"Small"

- Budget < $50 M
- Also typically collaborations < 100 people
- Sizes from grams to several tons

"New Approaches"

- Forward-looking (but did not include NP-funded experiments like $0\nu\beta\beta$ and neutrino mass)
- (Mostly) avoiding things that have already run
- Focused on physics of and with neutrinos; not additional physics capabilities
- Erred on the side of diversity over inclusivity of experiments

Still had to limit possibilities:

Point is not individual experiments but importance of the *program* of small-scale neutrino experiments.

But…

“Neutrinos don’t do anything…”

How can experiments be “small”?

- Increase the flux
  - Radioactive sources (e.g., ^{51}Cr)
  - Spallation/stopped π sources
  - Get close to reactors
  - Near detectors for beams
- Use high cross-section regimes
  - Collider energies
  - Coherent scattering
- Do neutrino experiments without neutrinos
  - Technology demonstrators
  - $0\nu\beta\beta$ (!) experiments
  - Direct neutrino mass measurements (!)
  - Measurements of hadron production or interactions

Why Small?

- Discovery opportunities
  - Particularly for BSM physics
- Engines of creativity
  - *New approaches* have to start small
  - (A lot easier to be creative when you don't have WBS 1.6.378.129.21…)
- Ownership
  - Chance to take necessary risks
  - Implement ideas without always *convincing* ***everyone***
  - People-driven, not purchase-order driven---important for workforce development
- Timeline
  - Often shorter than τ_{grad} or even $\tau_{post\text{-}doc}$
- Training
  - Experimental work =

Conception+Design+Construction+Commissioning+Acquisition+Analysis+Intepretation

Classes of Small ν Experiments

- Technology Demonstrators
- “Supporting” physics measurements
- Neutrino physics experiments

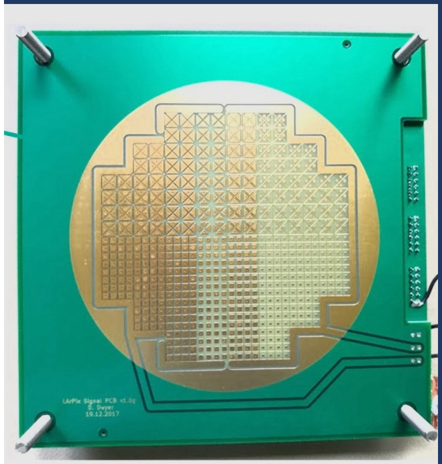
There are not fixed boundaries here…Often experiments are all three

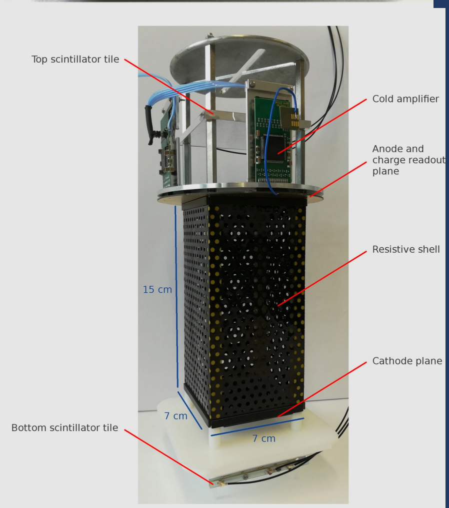
Technology Demonstrators

- Moving from “blue sky” R&D to experimental contexts (TRL6?)
- Sometimes associated with much larger projects (future or existing)
- But experiments in their own right!
- Sometimes project-managed but typically loosely
- Time scales are short! $< \tau_{grad}$ typically
- Often get re-used for physics measurements
- Sometimes part of a physics program via scaling

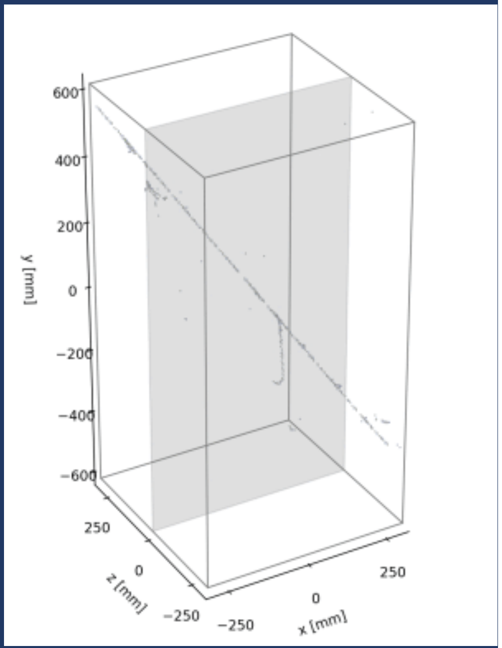
Technology Demonstrators

Pixellated LArTPCs





- Small pixels for big detectors
- Need low power to keep LAr cold
- Multiple technologies:
  - LArPIX
  - Qpix
  - Light+charge
- Improved 3D reconstruction
- Planning deployment at SNS for ν measurements
- To be used in DUNE ND-LAr
- Demonstrations eventually for DUNE Module 3
- These are typically kg to ton scale



Technology Demonstrators

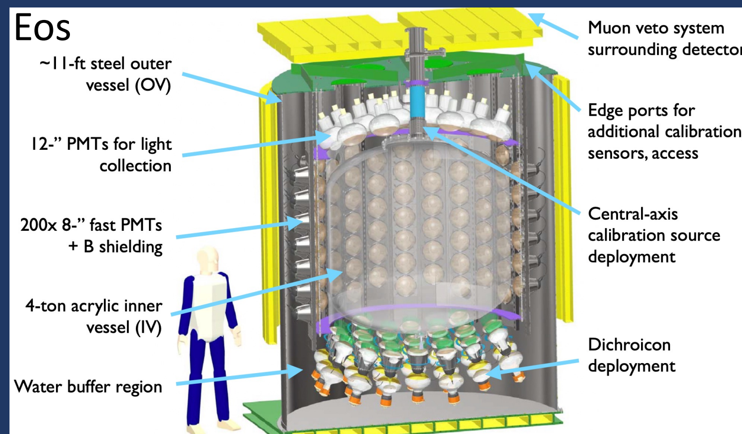
Hybrid Cherenkov/scintillation Detectors

NuDOT

Also:

- Isotopic loading development
- $2\nu\beta\beta$ spectra

Eos

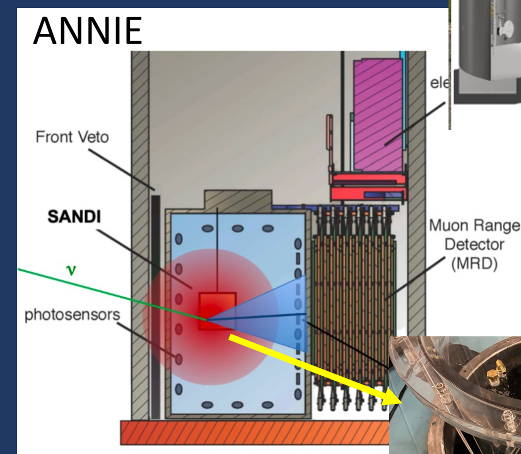


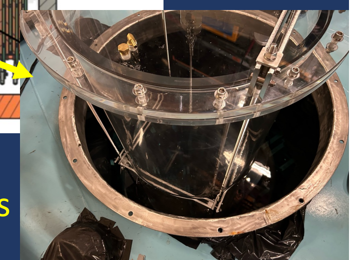
Possibly also:

- ^{7}Li SN ν cross sections at SNS
- Gallium anomaly test?
- 3-year timeline for design, construction, running….

BNL 30 t

ANNIE





Also:

- ν cross sections
- ν n production

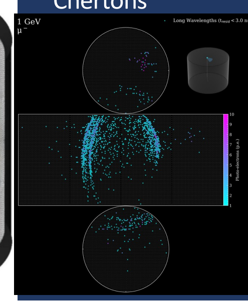
Technologies for experiments like Theia

- Fast timing (e.g., LAPPDs)
- Water-based liquid scintillator
- Spectral sorting with dichroicons
- New reconstruction techniques

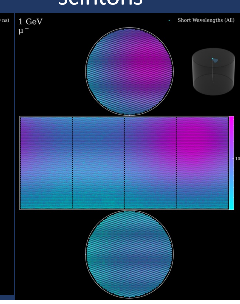
Theia25

Theia100

Chertons

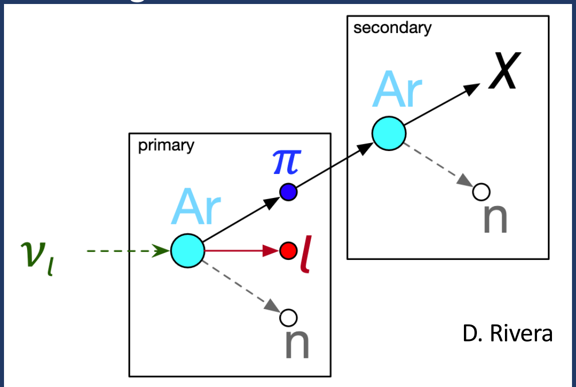


scintons



Supporting Measurements

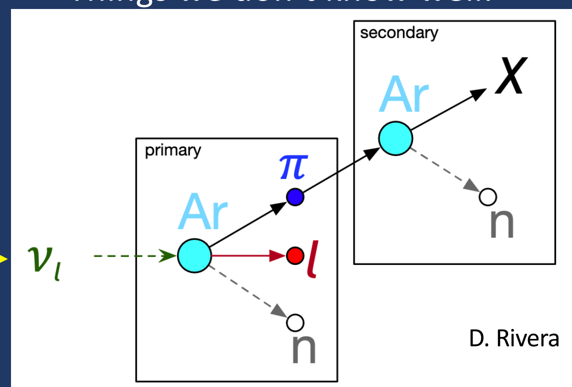
Things we don't know well:



Supporting Measurements

Things we don't know well:

How many of these are made



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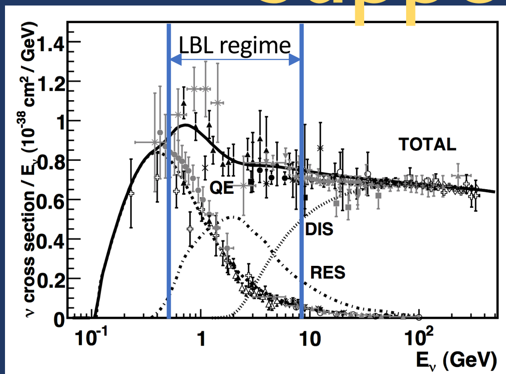

Formaggio and Zeller, Rev.Mod.Phys. 84 (2012) 1307-1341

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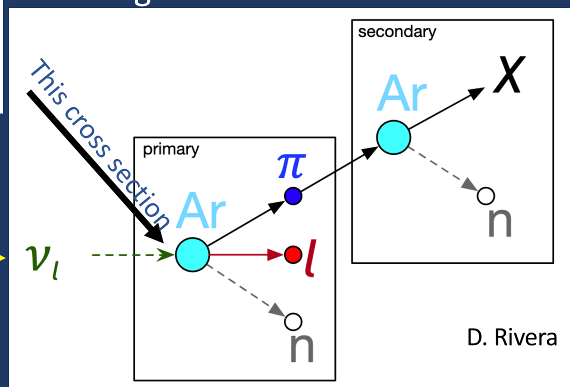
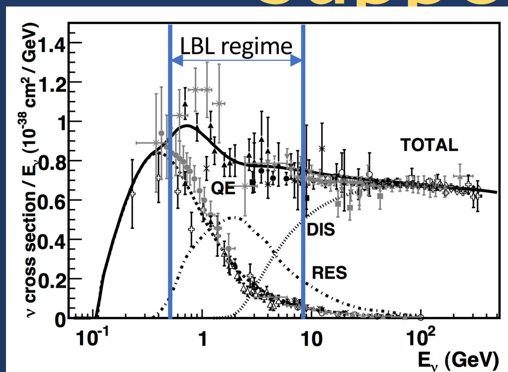


Supporting Measurements



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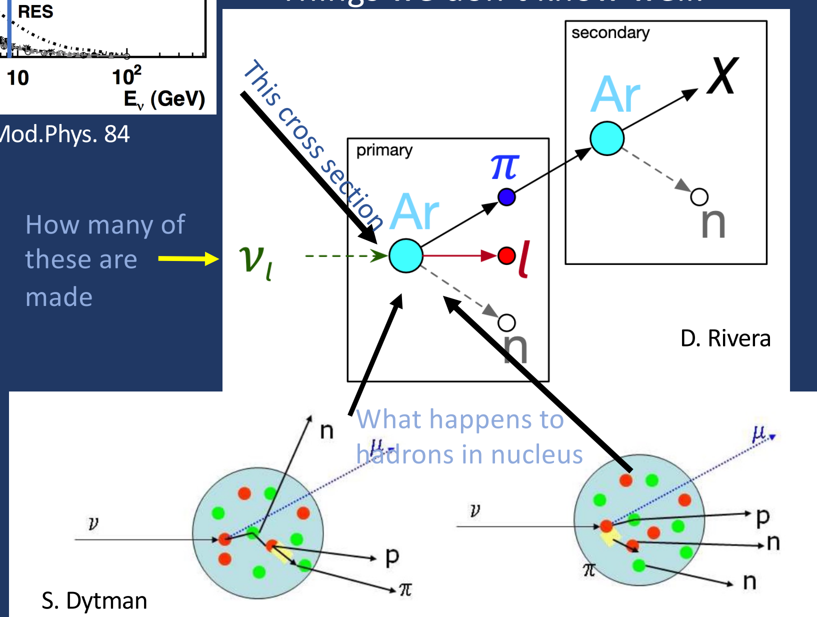
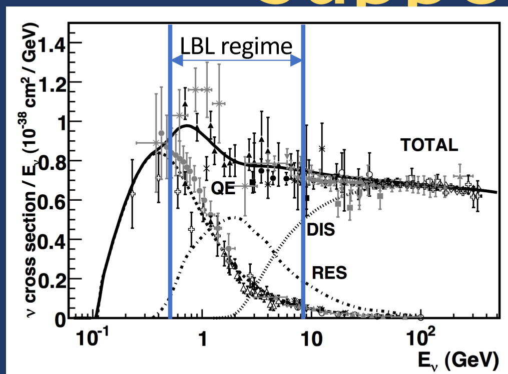


Supporting Measurements



Formaggio and Zeller, Rev.Mod.Phys. 84 (2012) 1307-1341

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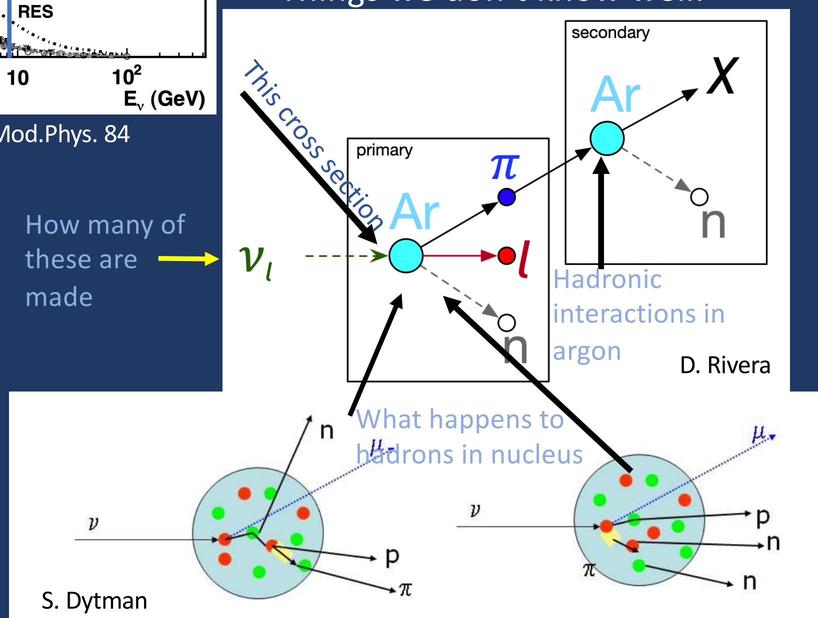
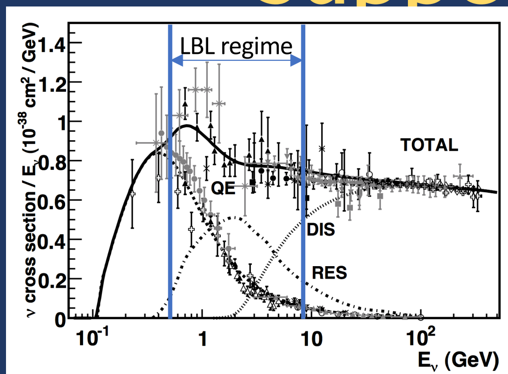


Supporting Measurements



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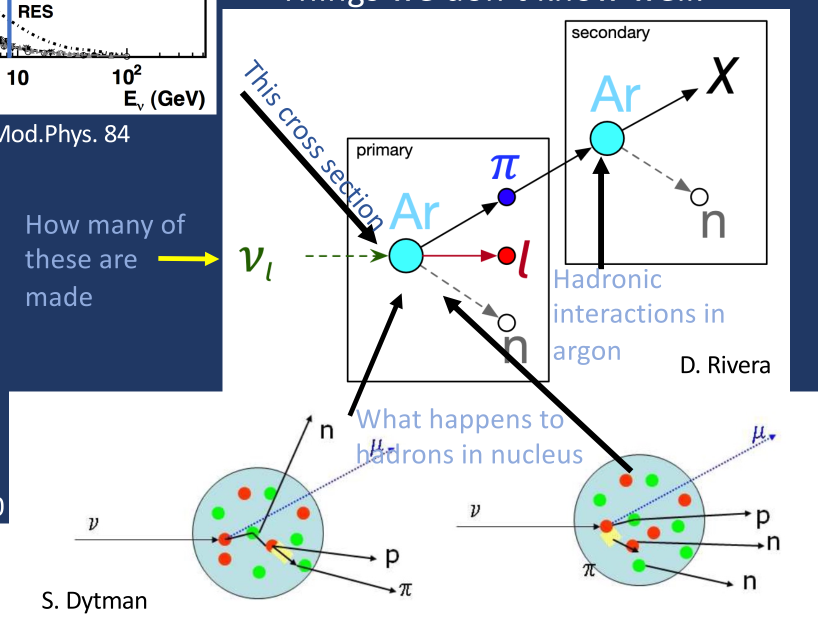


Opportunity for array of small-scale experiments with major contributions to broader n program

NOvA, Phys.Rev.Lett. 123 (2019) 15, 15180

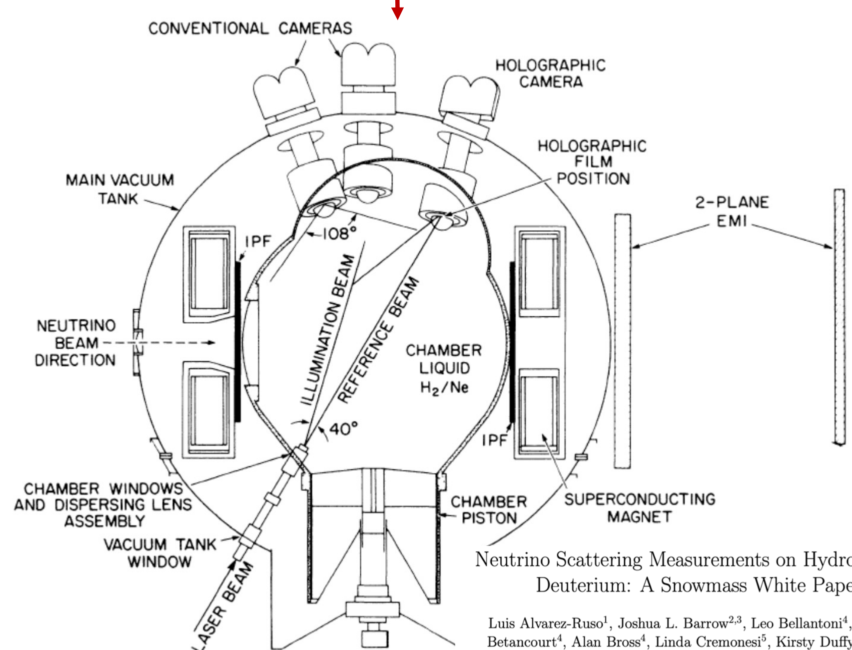
TABLE I. Systematic uncertainties on the total predicted numbers of signal and beam-related background events at the best fit point (see Table IV) in the ν_e selected samples in the neutrino and antineutrino datasets.

Source	ν_e Signal (%)	ν_e Bkg. (%)	$\bar{\nu}_e$ Signal (%)	$\bar{\nu}_e$ Bkg. (%)
Cross-sections	+4.7/-5.8	+3.6/-3.4	+3.2/-4.2	+3.0/-2.9
Detector model	+3.7/-3.9	+1.3/-0.8	+0.6/-0.6	+3.7/-2.6
ND/FD diffs.	+3.4/-3.4	+2.6/-2.9	+4.3/-4.3	+2.8/-2.8
Calibration	+2.1/-3.2	+3.5/-3.9	+1.5/-1.7	+2.9/-0.5
Others	+1.6/-1.6	+1.5/-1.5	+1.4/-1.2	+1.0/-1.0
Total	+7.4/-8.5	+5.6/-6.2	+5.8/-6.4	+6.3/-4.9

Supporting Measurements

(Modern!) H/D Bubble Chamber

(Not a modern bubble chamber)



- Interactions on H remove FSI and nuclear model
- On D, almost as good---simplest source of neutrons
- Existing measurements on H and D are decades old
  - Information on details is mostly lost
- New measurements would aim for ~1% level
- Relative simplicity of cross sections make BSM searches less systematically constrained
- 1 ton mass would yield 100x old sample statistics

Neutrino Scattering Measurements on Hydrogen and Deuterium: A Snowmass White Paper

Luis Alvarez-Ruso[1], Joshua L. Barrow[2,3], Leo Bellantoni[4], Minerba Betancourt[4], Alan Bross[4], Linda Cremonesi[5], Kirsty Duffy[6], Steven Dytman[7], Laura Fields[8], Tsutomu Fukuda[9], Diego González-Díaz[10], Mikhail Gorchtein[11], Richard J. Hill[12,4], Thomas Junk[4], Dustin Keller[13], Huey-Wen Lin[14], Xianguo Lu[15], Kendall Mahn[14], Aaron S. Meyer[16,17], Tanaz Mohayai[4], Jorge G. Morfín[4], Joseph Owens[18], Jonathan Paley[4], Vishvas Pandey[19], Gil Paz[20], Roberto Petti[21], Ryan Plestid[12,4], Bryan Ramson[4], Brooke Russell[17], Federico Sanchez Nieto[22], Oleksandr Tomalak[12,4,23], Callum Wilkinson[17], and Clarence Wret[24]

Interactions/year/ton D, FHC

process	ν_e	ν_μ	$\bar{\nu}_e$	$\bar{\nu}_\mu$
CCQE	2830	287000	394	9950
CCRES	5590	521000	862	18200
CCDIS	13000	592000	1990	32800
Total CC	21400	1400000	3250	61000
NCQE	1100	110000	183	5170
NCRES	2120	199000	371	8220
NCDIS	4146	211000	776	13100
Total NC	7520	520000	1330	26500

Supporting Measurements

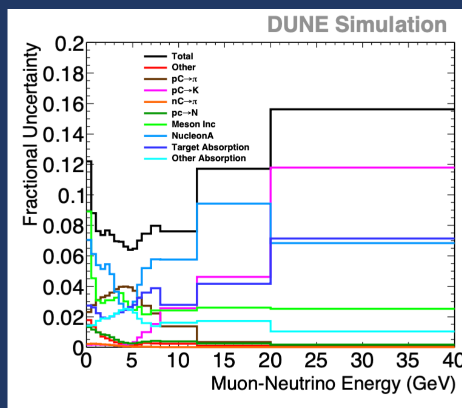
Hadron production measurements

EMPHATIC: A proposed experiment to measure hadron scattering and production cross sections for improved neutrino flux predictions

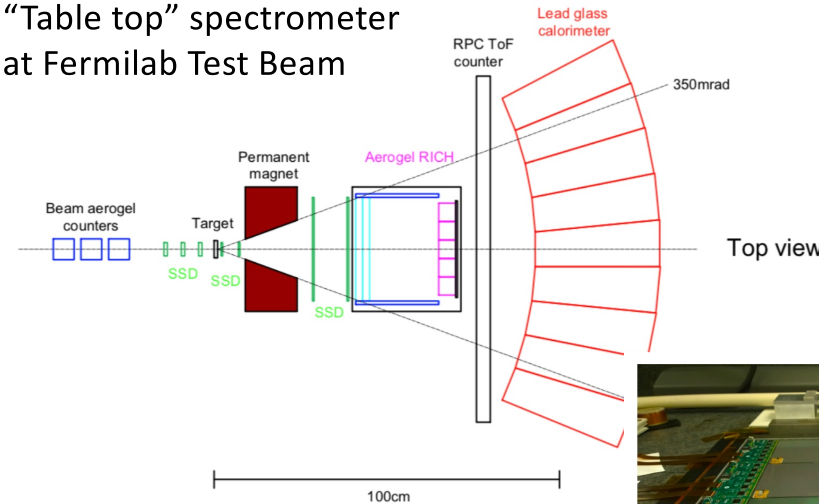
T. Akaishi,[12] L. Aliaga-Soplin,[4] H. Asano,[17] A. Aurisano,[3] M. Barbi,[14] L. Bellantoni,[4] S. Bhadra,[24] W-C. Chang,[24] L. Fields,[4] A. Fiorentini,[18] M. Friend,[5] T. Fukuda,[10] D. Harris,[4] M. Hartz,[7,20] R. Honda,[15] T. Ishikawa,[16] B. Jamieson,[23] E. Kearns,[1] N. Kolev,[14] M. Komatsu,[10] Y. Komatsu,[5] A. Konaka,[20] M. Kordosky,[22] K. Lang,[19] P. Lebrun,[4] T. Lindner,[23,20] Y. Ma,[17] D. A. Martinez Caicedo,[18] M. Muether,[21] N. Naganawa,[10] M. Naruki,[9] E. Niner,[4] H. Noumi,[13] K. Ozawa,[5] J. Paley,[4,*] M. Pavin,[20] P. de Perio,[20] M. Proga,[19] F. Sakuma,[17] G. Santucci,[24] T. Sawada,[11] O. Sato,[10] T. Sekiguchi,[5,†] K. Shirotori,[13] A. Suzuki,[8] M. Tabata,[2] T. Takahashi,[13] N. Tomida,[13] R. Wendell,[9] and T. Yamaga[17]
(The EMPHATIC Collaboration)

ν flux uncertainties large for both atmospheric ν and accelerator ν experiments---

Dominant source is hadron production uncertainties



"Table top" spectrometer at Fermilab Test Beam



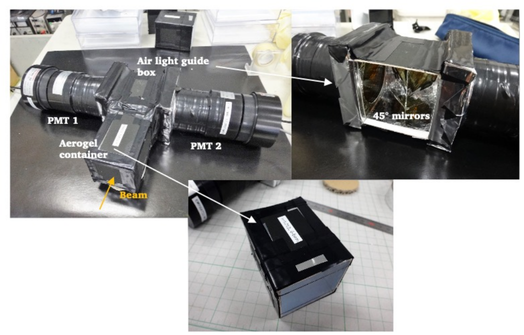


Figure 8. Photo of a Beam Aerogel Ckov detector prototype

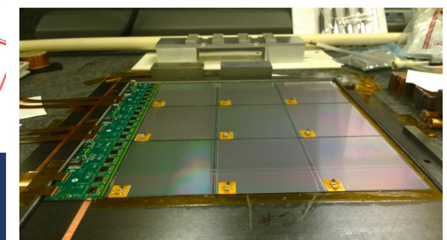


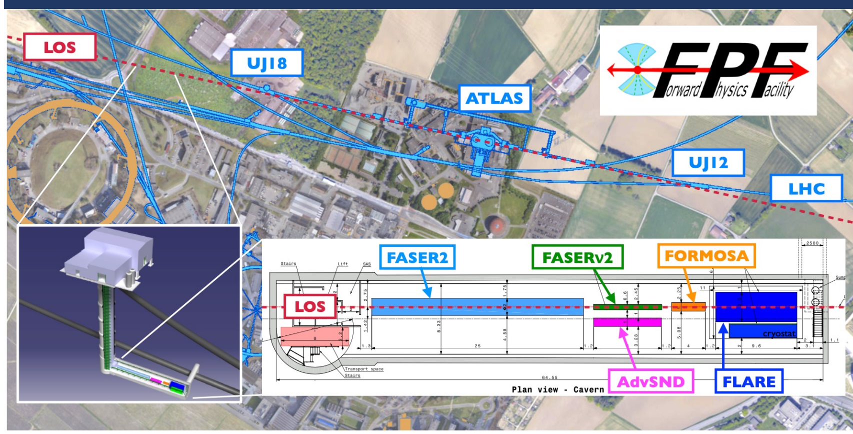
Figure 10. 30×30 cm^2 active area 122 μm pitch silicon strip detectors, to be used for downstream tracking.

Precision measurements help constrain ND measurements, atmospheric ν experiments

Supporting Measurements

Experiments at the Forward LHC Region

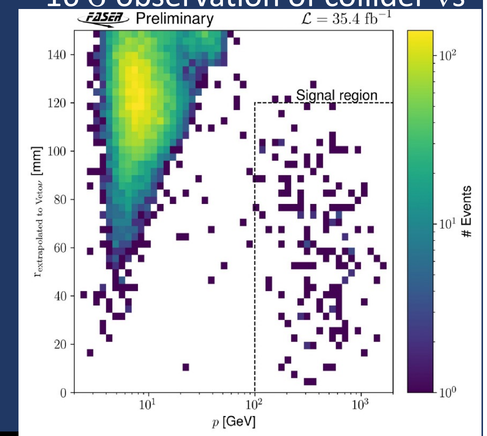
Neutrinos at TeV energies!



- Expect ~10^3 ν_τ
- New energy regime for direct cross section measurements
  - Relevant for neutrino telescopes
- Expect best limits on EM properties of ν_τs
- Tag interaction and detection vertices??

Hot off the presses…

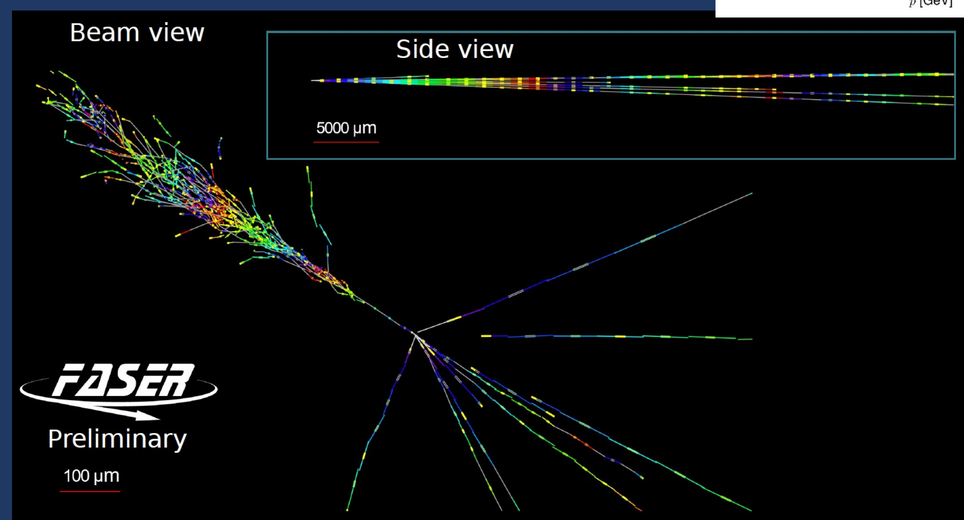
16 σ observation of collider νs



Technologically challenging on several fronts

Technology	FASER2	FASERnu2	Adv-SND	FLArE	FORMOSA
Large aperture SC magnet	x				
High resolution tracking	x		x	x	
Large scale emulsion		x			
Silicon tracking			x		
High purity noble liquids				x	
Low noise cold electronics				x	
Scintillation				x	x
Optical materials				x	x
Cold SiPM				x	
Picosec synchronization			x	x	x
Intelligent Trigger	x		x	x	x

Table 5: Enabling technologies for the detectors and systems of the far forward physics facility.



Neutrino Physics

- Physics *of neutrinos* and *with neutrinos*
- Hard for small experiments to compete for “standard” oscillation physics
  - Oscillations ~ (Δm^2 L/E)
  - Small experiments need small L to get enough rate
  - Known Δm^2s mean E too small
- But BSM physics may have much bigger Δm^2
- Or show up in deviations from known cross sections

Neutrino Physics

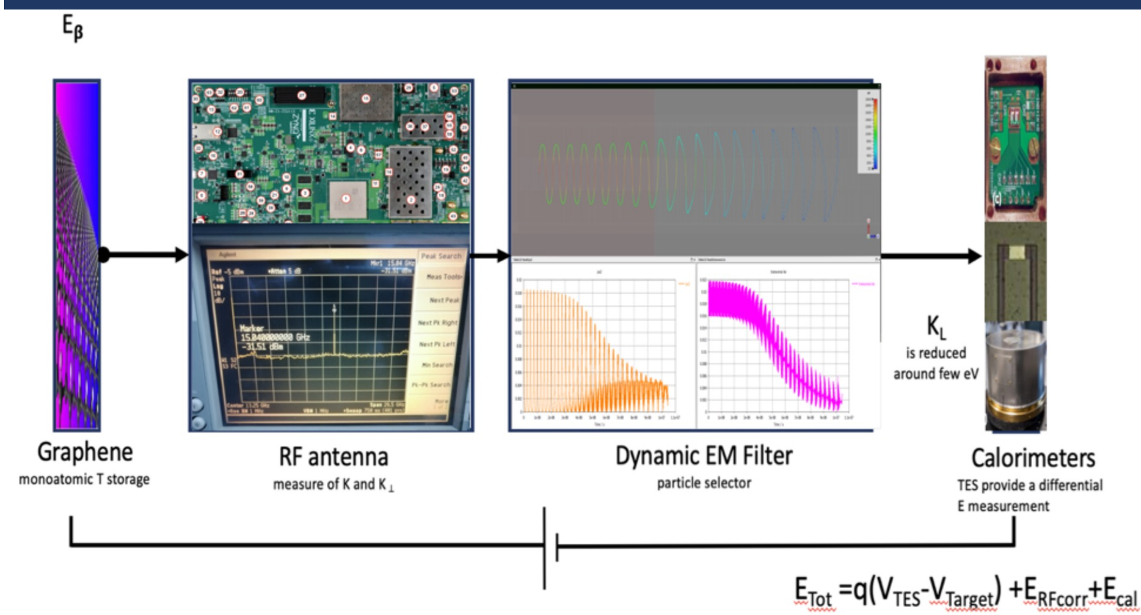
PTOLEMY

About as ambitious as it gets: Detection of CνB! $T_\nu \sim 1.7\times10^{-4}$ eV

Threshold on β-decaying nuclei $\nu_e + N \rightarrow N'$+e is zero…but lots of β-decays happening…

Neutrino mass means β-spectrum ends "early" and e has another m_ν of energy, so…

So all that is needed is **sub-eV** energy resolution.



Achieved by:

- Graphene substrate for 100 g tritium source
- Need μHZ of background
- Multiple spectrometer stages
  - MAC-E filter
  - Cryogenic calorimetry
  - RF tracking/TOF

PTOLEMY: Towards Direct Detection of the Cosmic Neutrino Background

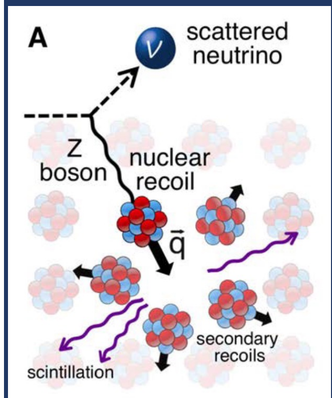
Snowmass 2021 Letter of Intent

LOI Supporters and the PTOLEMY Collaboration

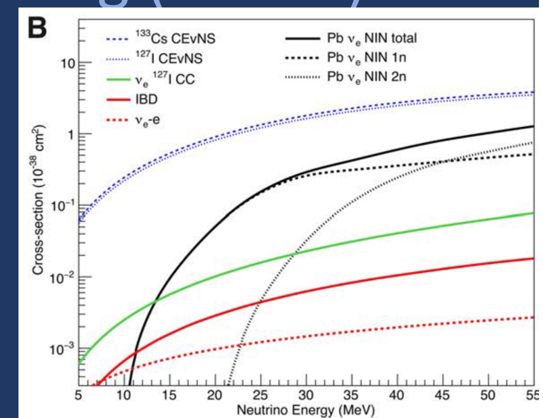
M.G. Betti[10,11], M. Biasotti[4], A. Boscá[17], F. Calle[17], J. Carabe-Lopez[15], G. Cavoto[10,11], C. Chang[24,25], W. Chung[28], A.G. Cocco[6], A.P. Colijn[14], J. Conrad[20], N. D'Ambrosio[2], P.F. de Salas[18,20], M. Faverzani[5], A. Ferella[20], E. Ferri[5], L. Ficcadenti[10,11], P. Garcia-Abia[15], G. Garcia Gomez-Tejedor[16], S. Gariazzo[18], F. Gatti[4], C. Gentile[27], A. Giachero[5], J.E. Gudmundsson[20], Y. Hochberg[1], Y. Kahn[25,26], M. Lisanti[28], C. Mancini-Terracciano[10,11], G. Mangano[6], L.E. Marcucci[8,9], C. Mariani[11], J. Martínez[17], M. Messina[2], A. Molinero-Vela[15], E. Monticone[13], A. Nucciotti[5], F. Pandolfi[10], S. Pastor[18], J. Pedrós[17], C. Pérez de los Heros[21], O. Pisanti[6,7], A.D. Polosa[10,11], A. Puiu[5], I. Rago[10,11], Y. Raitses[27], M. Rajteri[13], N. Rossi[10], A. Ruocco[12], R. Santorelli[15], K. Schaeffner[3], C.F. Strid[19,20], A. Tan[28], C.G. Tully[28], F. Zhao[28], K.M. Zurek[22,23]

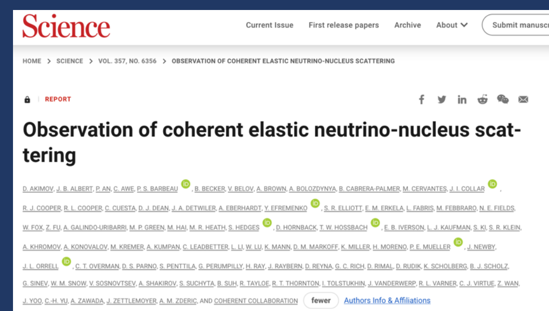
Neutrino Physics

Coherent Elastic Neutrino Nucleus Scattering (CEνNS)



- Standard model calculable cross section (with knowledge of neutron density)
- Big cross section! (for neutrinos…) Goes like ~A^2
- Pure neutral current!
- But recoil energies range from tiny to *really* tiny…keV energies





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HOME > SCIENCE > VOL. 357, NO. 6356 > OBSERVATION OF COHERENT ELASTIC NEUTRINO-NUCLEUS SCATTERING

REPORT

Observation of coherent elastic neutrino-nucleus scattering

D. AKIMOV, J. B. ALBERT, P. AN, C. AWE, P. S. BARBEAU, B. BECKER, V. BELOV, A. BROWN, A. BOLOZDYNYA, B. CABRERA-PALMER, M. CERVANTES, J. I. COLLAR, R. J. COOPER, R. L. COOPER, C. CUESTA, D. J. DEAN, J. A. DETWILER, A. EBERHARDT, Y. EFREMENKO, S. R. ELLIOTT, E. M. ERKELA, L. FABRIS, M. FEBBRARO, N. E. FIELDS, W. FOX, Z. FU, A. GALINDO-URIBARRI, M. P. GREEN, M. HAI, M. R. HEATH, S. HEDGES, D. HORNBACK, T. W. HOSSBACH, E. B. IVERSON, L. J. KAUFMAN, S. KI, S. R. KLEIN, A. KHROMOV, A. KONOVALOV, M. KREMER, A. KUMPAN, C. LEADBETTER, L. LI, W. LU, K. MANN, D. M. MARKOFF, K. MILLER, H. MORENO, P. E. MUELLER, J. NEWBY, J. L. ORRELL, C. T. OVERMAN, D. S. PARNO, S. PENTTILA, G. PERUMPILLY, H. RAY, J. RAYBERN, D. REYNA, G. C. RICH, D. RIMAL, D. RUDIK, K. SCHOLBERG, B. J. SCHOLZ, G. SINEV, W. M. SNOW, V. SOSNOVTSEV, A. SHAKIROV, S. SUCHYTA, B. SUH, R. TAYLOE, R. T. THORNTON, I. TOLSTUKHIN, J. VANDERWERP, R. L. VARNER, C. J. VIRTUE, Z. WAN, J. YOO, C.-H. YU, A. ZAWADA, J. ZETTLEMOYER, A. M. ZDERIC, AND COHERENT COLLABORATION

fewer | Authors Info & Affiliations

2017 observation of process by COHERENT has led to an explosion of new low-threshold work:

Experiment	Enabling technology	E_{th}(NR)	target material	mass	status	ν source
MINER [105]	phonon detectors	$\mathcal{O}$(100eV)	Ge, Al_2O_3	$\mathcal{O}$(100g)	D/C	R
NUCLEUS [106–108]	phonon detectors	$\mathcal{O}$(10eV)	$CaWO_4$,Al_2O_3	$\mathcal{O}$(10g)	D/C	R
RICOCHET [109]	phonon detectors	$\mathcal{O}$(10eV)	Ge, Zn	$\mathcal{O}$(1kg)	D/C	R
BULLKID [110]	phonon detectors	$\mathcal{O}$(10eV)	Si	$\mathcal{O}$(10g)	R&D	-
CONNIE [111]	CCD sensors	$\mathcal{O}$(100eV)	Si	$\mathcal{O}$(100g)	run	R
COHERENT [112]	cryog. scintillator	$\mathcal{O}$(1keV)	CsI	$\mathcal{O}$(10kg)	D/C	S
COHERENT [112]	HPGe	$\mathcal{O}$(1keV)	Ge	$\mathcal{O}$(10kg)	D/C	S
COHERENT [112]	scintillator	$\mathcal{O}$(1keV)	NaI	$\mathcal{O}$(1ton)	D/C	S
CONUS [113]	HPGe	$\mathcal{O}$(1keV)	Ge	$\mathcal{O}$(1kg)	run	R
Dresden [114]	HPGe	$\mathcal{O}$(1keV)	Ge	$\mathcal{O}$(1kg)	run	R
nuGen [115]	HPGe	$\mathcal{O}$(1keV)	Ge	$\mathcal{O}$(1kg)	run	R
TEXONO [116]	HPGe	$\mathcal{O}$(1keV)	Ge	$\mathcal{O}$(1kg)	run	R
NEON [117]	scintillator	$\mathcal{O}$(1keV)	Ge	$\mathcal{O}$(10kg)	run	R
SBC [118]	bubble	$\mathcal{O}$(100eV)	lAr(Xe)	$\mathcal{O}$(10kg)	R&D	R
NEWS-G [119]	gaseous	$\mathcal{O}$(100eV)	Ne,CH_4	$\mathcal{O}$(100g)	run	-
COHERENT [120]	liquid noble	$\mathcal{O}$(1keV)	lAr	$\mathcal{O}$(10kg)	run	S
RED100 [121]	liquid noble	$\mathcal{O}$(1keV)	lXe	$\mathcal{O}$(100kg)	run	R
CHILLAX [122]	liquid noble	$\mathcal{O}$(100eV)	lAr,lXe	$\mathcal{O}$(10kg)	R&D	R/S
NUXE [123]	liquid noble	$\mathcal{O}$(100eV)	lAr,lXe	$\mathcal{O}$(10kg)	R&D	R

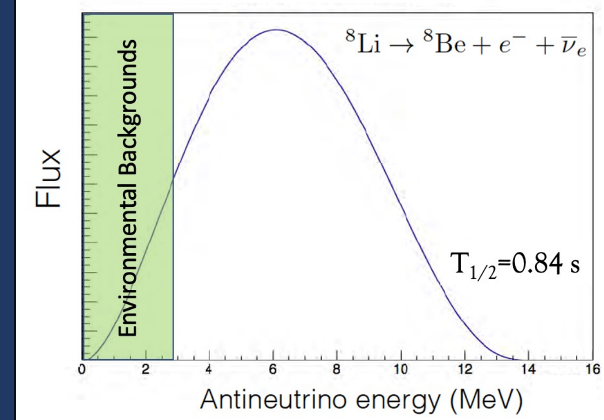
- Searches for sterile via NC “disappearance”
- Constraining non-standard interactions
- Cross sections for other experiments (e.g., DM)
- Big push for detection at reactors: all coherent
- Also big push to move to more precision

Neutrino Physics

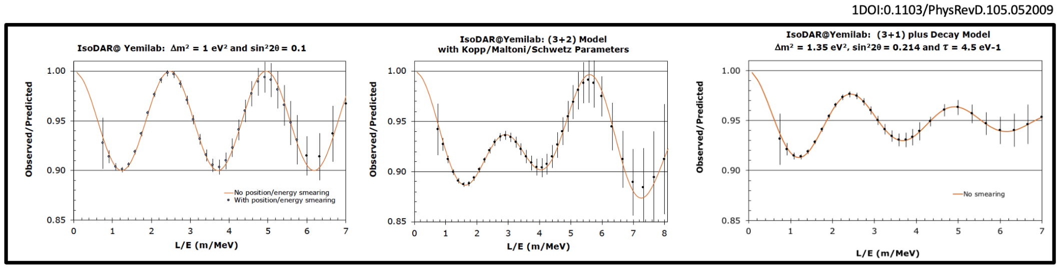
ISODAR

New approach to neutrino beam: cyclotron production of ^{8}Li

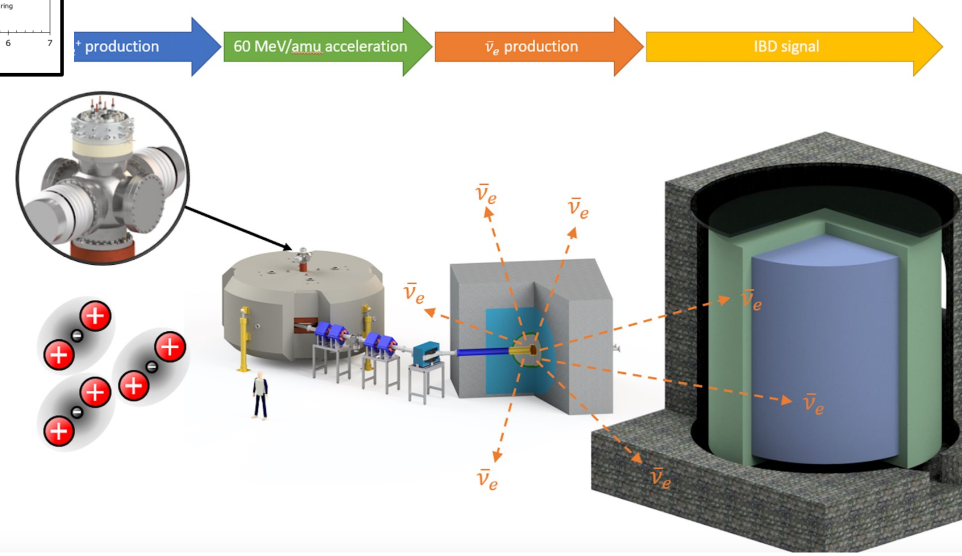
- Pure high(ish) energy anti-ν_e beam
- Deployment at South Korea's Yemilab with LS detector target
- Short-baseline oscillation anomaly sensitivity



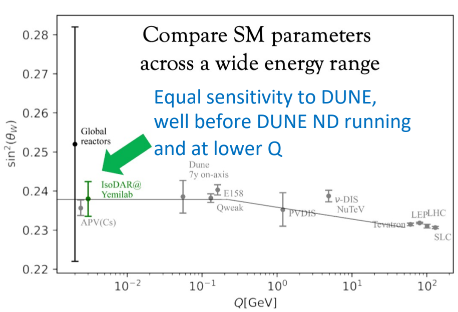
1DOI:0.1103/PhysRevD.105.052009



- 5 year timeline
- Big university involvement and leadership



- And precision tests for new physics



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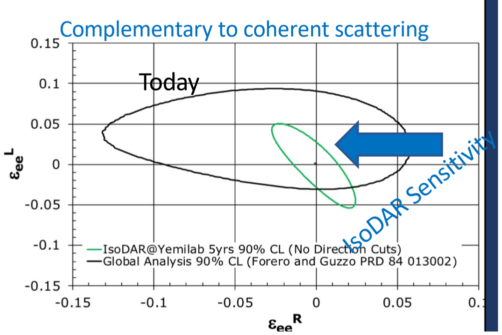
Search for deviations in the cross section energy dependence due to new interactions



Summary

- Small-scale experiments are critical for the health of ν Frontier
- Opportunities for discovery
- Critical measurements for mid- and large-scale experiments
- Pursuit of exciting and creative ideas
- Program is broad and rich
- Excellent opportunities for workforce training and development